Ka-Band Propagation Research Using ACTS

F. Davarian

Abstract

The congestion of the radio spectrum below about 18 GHz is causing a rush of interest in the 20/30-GHz band. Due to the shorter wave length of these frequencies, the atmosphere, especially rain, greatly influences the transmission of signals between Earth/space stations. The slant path effects in the Ka region of the radio spectrum are addressed and an experimental campaign for collection propagation data is described. This campaign uses the Advanced Communications Technology Satellite (ACTS) and consists of several measurement sites.

A brief description of the spacecraft payload and the propagation terminals is given. The experiment sites are discussed. The expected outputs of the ACTS campaign are presented. Measured results and analyzed data are reported.

Introduction

There are strong indications that the 20/30-GHz[1] frequency band will soon be fully exploited for Earth/space applications. Interest in the commercial sector is rapidly rising. Two of the proposed big low-Earth-orbit (LEO) systems, iridium and odyssey, will use 20/30-GHz feeder links. Moreover both Spaceway and Teledesic communication satellite systems will use Ka-band frequencies as their primary links. This region of the radio spectrum is also popular in the noncommercial sector. The next generation of tracking and data relay satellites (TDRS) will use this band on an experimental basis; NASA is strongly considering the use of frequencies slightly above 30 GHz for its deep space missions; and the U.S. military is already using 20- and 40-GHz links in its Milstar system.

The 20/30-GHz radio-frequency region offers three advantages for satellite communications over the lower frequencies of C and K_u bands. These benefits can be summarized as spectrum availability, reduced interference potential, and reduced equipment size. However, these benefits of the K_a band are not without a cost. The 20/30-GHz band is more susceptible to tropospheric impairment than the lower frequencies. Mitigating these tropospheric-induced losses, which can be accomplished at lower frequencies by providing a modest link margin, requires a more elaborate approach at the Ka-band.

To combat the effect of the Earth's atmosphere on 20/30-GHz frequencies, a good understanding of the phenomenon is required. It is important that the

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[1] in this paper, *20/30 GHz* and *Ka-band* are used interchangeably to indicate the frequency band from about 18 to about 32 GHz.

propagation limitations of this band arc recognized and that they are accounted for in system planning and design. For example, the link avail ability requirement for the Ka band should either be relaxed, or a technique other than the mere usc of a link power margin should be employed. To increase our understanding of Ka-band propagation effects, two experimental campaigns were implemented during the last decade. The first of these efforts was the Olympus propagation experiment that took place mainly in Europe from 1988-1992. This experiment used the Ku- and Ka-band signals of the Olympus spacecraft for field measurements [1]. The Ol ympus experiment recentl y conclud ed and its results were published [2]. The second effort is called the Advanced Communication Technology Satellite (ACTS) propagation campaign that uses 20- ant] 27.5-GHz signals transmitted from the ACTS satellite. This paper will discuss the ACTS propagation campaign which began in 1993[2].

Objectives of the ACTS Propagation Campaign

The objectives of this campaign arc stated as follows:

- To provide a good understanding of Ka-band propagation issues
- To develop models for the prediction of propagation -relat ed anomalies
- To develop tools for the mitigation of these anomalies

These objectives will be achieved by making lon~,-term measurements at multiple sites and analyzing the collected data. Clearly, a timely and full dissemination of the results to the users of propagation data, i.e., the satellite communications community, is a prerequisite for the successful accompli shment of the above objectives.

Ka-Band Propagation issues

For the sake of completeness, the primary Ka-band propagation effects arc listed below:

Rain A ttenuation. Signal attenuation due to rain is the most severe propagation effect at Ka-band. This kind of loss can exceed 20 dB for small percentages of time.

Gaseous A bsorption. A loss close to 1 dB can be associated with oxygen and water vapor absorption.

Cloud Attenuation. Clouds along the propagation path can attenuate Ka-band frequencies. Typical values arc in the order of 1 dB or more.

Scintillation. This term refers to rapid fluctuations of signal amplitude (and phase). It is caused by time-varying changes in the refractive index of the atmosphere. 1 t can also be caused by rain storms.

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[2] Mobile experiments arc not discussed in this paper.

Depolarization. A transfer of energy from one polarization state into its orthogonal state can be caused by the atmosphere, mainly clouds and rain.

Atmospheric Noise. The atmosphere has an equivalent black body temperature. At Ka-band frequencies, this temperature varies from about 10 K to close to the ambient temperature.

Wet Antenna and Snow on the Antenna. Condensation and snow on the antenna cause signal losses. These losses can be as large as a few dB.

Reliable statistics are needed to predict the above effects for slant-path applications. Note that each effect is not only a function of frequency, but also of location, path elevation angle, and season (time). Since it is not possible to make observations at every location, the region of interest can be divided into several rain or atmospheric climate zones. A climate zone is an area on the ground that has a certain statistical attribute. For example, the characteristic that *rain rates exceeding a given threshold occur at a certain probability* would constitute a rain climate zone.

Background

As a part of its space commercialization program, the National Aeronautics and Space Administration (NASA) has supported slant-path propagation studies and experiments for more than two decades. The NASA Propagation Program identifies research topics that are important to the development of new space applications. This program also funds the investigation of these topics by the experts. Since propagation research includes field measurements, the NASA Propagation Program searches for satellites of opportunity for data collection.

ACTS is a platform of opportunity for the propagation community because it allows dual-frequency field measurements. The satellite is equipped with a pair of beacon transmitters at 20 and 27.5 GHz, providing ample signal power for reception in most parts of North America. The 1993 launch date of ACTS ideally coincided with a rise in interest in the Ka portion of the radio spectrum. Considering that the majority of the proposed Ka-band systems will be launched at the turn of the century, ACTS timing is convenient for collecting valuable propagation data.

Recognizing its potential for propagation studies, the NASA Propagation Program began planning to use ACTS in 1987. In 1989, NASA formally announced its decision to support propagation measurements by sponsoring the first ACTS Propagation Studies Workshop attended by representatives from industry, academia, and other users of propagation data. The goals of the ACTS propagation campaign were defined in this workshop and a plan was drafted by the participants. In subsequent workshops, this plan was refined and the requirements of the propagation terminal and the data-collection software were written. In parallel with these planning activities, NASA released an Announcement of Opportunity for an experiment in December 1991. This announcement resulted in the selection of seven experimenters in North America that would use NASA-provided terminals for field measurements. A few months before the experimenter selection process began, NASA funded Virginia Polytechnic Institute and State University (VPI) to build seven ACTS propagation terminals for delivery to the selected experimenters. As mentioned earlier, the requirements for these terminals had been established at ACTS Propagation Studies Workshops. The propagation terminals were delivered about the same time that ACTS was launched, September 1993. After terminal installation and testing, the data-collection phase of the ACTS propagation campaign formally began on December 1, 1993.

The Spacecraft Payload

The ACTS propagation payload consists of a pair of vertically polarized 20- and 27-GHz beacon subsystems, known as downlink and uplink beacons, respectively. Each subsystem is backed up with a spare, with the 20-GHz spare horizontally polarized. The uplink beacon is a pure CW transmission, whereas the downlink beacon is modulated by ranging tones and low bit-rate telemetry. However, the design of the downlink beacon incorporates *place holder tones* to prevent a change in the power level of the carrier when ranging signals are turned on. Figure 1 shows the measured power spectral density of the downlink beacon. This figure shows that the downlink beacon consists of a carrier, a pair of 32-kHz place holder tones, and a pair of 64-kHz telemetry subcarriers for low bit-rate telemetry data.

Figures 2-a and 2-b show the radiation patterns of the vertically-polariz.cd downlink and uplink beacons, respectively, as viewed on the ground, satellite longitude 100° W. The horizontal and vertical axes give the azimuth and elevation of the view point on the ground with respect to the antenna axes. It appears that the contiguous U.S. and most of Alaska, Canada, and northern Mexico are covered. The maximum effective isotropic radiated power (EIRP) values of the 20- and 27.5 -GHz beacons are approximately 22 and 19 dBW, respectively.

Propagation Terminals

The requirements of the ACTS propagation terminal (APT) were developed by participants of the ACTS Propagation Workshops. The motivation in introducing these requirements were (a) to accomplish the goals of the campaign, and (b) to keep the costs down. The design of the terminal is based on dual-frequency reception using digital signal-processing technology and dual-frequency radiometry for the determination of the absolute atmospheric-induced signal loss value. The APT was designed and manufactured by the Satellite Communications Group at Virginia Polytechnic Institute and State University, Blacksburg, VA.

The APT uses a small dual-frequency (20- and 27.5 -GHz) antenna and a front end shared by the beacon and the total-power radiometer receivers. The radio frequency (RF) front-end enclosure is carefully temperature controlled to ensure radiometer stability. A simplified block diagram of the APT is shown in Figure 3. Salient features of the terminal areas follows:

- *1.2-m common* antenna for both 20- and 27.5-GHz beacons
- Ortho-mode transducer (OMT) to separate the 20- and 27-GHz signals
- Preamplifiers followed by single downconversion to 70-MHz intermediate frequency (IF)
- Digital beacon receivers to measure signal power
- Total-power radiometers with sensitivity of 1 K
- PC-based data-collection system

The output of the 70-MHz IF signal is split into two paths. in one path, the signal is further downconverted to 455 kHz. The 455-kHz signal drives the digital receiver. The digital receiver performs a fast Fourier transform (FFT) of the signal over a 200-kHz band during acquisition to locate the beacon signal. In the operational (tracking) mode, a narrow-band FFT is used to drive a frequency - tracking loop. A major advantage of the digital receiver is that it acquires the signal in less than 3 seconds from any point within the 200-k Hz bandwidth and reliably locks to the carrier component of the complex modulated beacon signal. If the signal is lost in a deep fade, it will be acquired as soon as the attenuation is less than about 25 dB. The overall accuracy of the receivers is estimated to be better than 0.5 dB.

The second path of the 70-MHz IF output signal feeds the radiometer. The radiometer measures the noise power over a 50-MHz bandwidth. Calibration is performed automatically at frequent intervals by switching a low-loss coaxial switch ahead of the mixer to the RF noise diode in series with an attenuator.

The PC-based data acquisition and control system (DACS) consists of three major components: data acquisition and control hardware, a personal computer, and software programs for data collection and data editing. The data acquisition and control hardware is located in the IF chassis and collects data from beacon receivers, radiometers, environmental instruments, and system temperature sensors. This subsystem also controls the calibration of the radiometer channels.

The PC hardware receives all data transmitted from DACS, logs the data to disk, and displays the collected data for user viewing. The PC is placed indoors, while the rest of the DACS is located outdoors in the IF chassis. Table 1 shows the signals collected by DACS and their corresponding data rates. The APT power budget is given in Table 2.

Table 1. Signals Collected by DACS

Data	Rate	Comment
Time Stamp	4 Bytes/s	
27-GHz Beacon (1 Hz)	2 Bytes/s	
20-GHz Beacon (1 Hz)	2 Bytes/s	
27-GHz Radiometer (1 Hz)	2 Bytes/s	
27-GHz Radiometer (1 Hz)	2 Bytes/s	
Environmental Sensors and Status	4 Bytes/s	Rain, temperature, wind, and barometric pressure
TOTAL	16 Bytes/s	1.32 MBytes per day

Tat-de 2. ACTS Propagation Terminal Power Budget Computed for Blacksburg, Virginia (North Latitude 37.23 deg, West Longitude 80.44 deg)

Frequency	GHz	20,185	27.505
EIRP toward Blacksburg	dBW	20.70	16.50
Modulation loss	dB	3.20	0.00
EIRP at Blacksburg	dBW	17.50	16.50
Path loss	dB	210.07	212.76
Clear sky attenuation	dB	0.95	0.70
Antenna efficiency	%	0.65	0.65
Antenna gain (1.22 m)	dB	46.36	49.05
Antenna temperature	K	100.00	100.00
Pointing loss	dB	0.1	0.1
Power available from antenna	dBW	-147.26	-148.01
System noise temperature	K	1645.32	1677.49
G/T	dB/K	14.19	16.80
C/N_o	dB	49.18	48.34
C/N in a 20-Hz bandwidth	dB	36.17	35.33

Table 2 indicates that receiver fade margin, is close to 30 dB for both frequencies at Blacksburg, VA.

Figure 4 shows the ACTS Propagation Terminal. The RF portion is behind the antenna feed; the IF portion is in the box placed on the ground. The indoor portion, i.e, the personal computer, is not shown, Although other terminals arc also used in this campaign, the seven APT's constitute the backbone of the ACTS propagation campaign.

Calibration and I'reprocessing

The propagation terminals generate daily output files containing one-second averages of the beacon received power levels, radiometer voltages and one-minute averages of surface meteorological observations co] lected by the environmental sensors. A preprocessing program converts the recorded radiometer data into one-second-average attenuation estimates, combines these estimates with the beacon power level measurements to provide estimates of the unattenuated satellite beacon power levels radiated toward the propagation terminal, predicts the unattenuated beacon reference power levels for attenuation determination, and outputs both the radiometer and beacon attenuation estimates for further processing.

The preprocessing program also performs the periodic radiometer channel calibrations to maintain precise radiometer power level estimates based on the radiometer voltage measurements. The program also uses the surface meteorological observations to generate medium temperature estimates for the conversion of radiometer power measurements into attenuation estimates and to generate sky brightness temperature estimates for the calibration of the radiometer channels during periods with neither rain nor clouds.

The radiometer system is calibrated by adjusting the effective antenna efficiency values to make the changes in estimated attenuation from the radiometers match the observed changes in beacon attenuation for attenuation values between 3 and 6 dB and by correcting for the sidelobe contributions to the radiometer power measurements to make the radiometer estimates of sky brightness temperatures match the expected values calculated for cloud free conditions as estimated from the surface meteorological observations. The resulting uncertainty in the radiometer estimates of total attenuation for periods with neither rain nor clouds is less than 0.3 dB.

The beacon derived attenuation estimates depend upon an adequate estimate of the beacon reference power level that adjusts for the diurnal and shorter term variations of power radiated by the satellite and removes the power level changes at 20 GHz generated by changes in beacon modulation. The preprocessing program automatically y removes the modulation changes. The reference level estimates are based on a fourth order harmonic curve fit to the reference level for the prior day with a one-hour ahead prediction of the differences between the smoothed curve fit and weighted observations from a four-hour period prior to making the predictions, The prediction of a least squares correction for differences between the smoothed estimate of the diurnal variation and the observed reference level is required to provide an adequate c st imate of the reference level during periods with severe attenuation. Observations using the prediction and correction scheme show worst case attenuation estimation errors of less than 0.5 dB during periods of rapid change when the earth eclipses the sun at the satellite.

Statistically, for a month of observations, the differences between the radiometer attenuation distribution estimates and the beacon attenuation distribution estimates are less than 0.1 dB for attenuation levels less than 5 dB. This calibration scheme amounts to a least squares fitting of the beacon attenuation estimates to the radiometer attenuation estimates over a sliding intervals of about four hours. The result is an estimate of the total attenuation due to all causes: rain, clouds, scintillation, wet antenna, or wet snow on the antenna.

Experiment Sites and the ACTS Data Center

In addition to the technical merit of their proposals, geographical diversity was also a criterion in the selection of the ACTS propagation experimenters. The selected sites generally represent different climate regions of North America. The Radiocommunication Sector of the international Telecommunication Union (ITU-R) divides the North American continent into a number of rain climate zones. Figure 5 shows the location of the seven ACTS propagation sites superimposed on the ITU-R climate zones, and includes a table that defines these climate zones. Table 3 lists these sites with their geographical attributes.

The investigators of these sites are funded by NASA to collect and analyze data for two years. Every month the collected raw and processed data are sent to the ACTS Data Center at the University of Texas, Austin. The collected data include 20- and 30-GHz beacon and radiometer measurements, rain rate measurements, and other environmental data.

Table 3. ACTS Propagation Measurement Sites

Location	**ITU-R Rain Zone**	**Lat. (North), deg**	**Long. (West), deg**	**Az. from North, deg**	**Path Elevation deg**
Vancouver, BC	D	49	123	150	30
Ft. Collins, CO	E	40	105	173	43
Fairbanks, AL	C	65	148	129	9
Reston, VA Clarksburg, MD[1] Laurel, MD[1]	K	39	077	214	39
Las Cruces, NM	M/E	32	107	168	51
Norman, OK	M	35	097	184	49
Tampa, FL	N	28	082	214	52

[1]Used in the diversity experiment; the terminal is supplied by the experimenter.

The data center receives monthly data from the seven sites and performs an independent audit for data quality. The result of this data audit is shared with the corresponding site, Another function of the data center is data archiving. Measurements received from all the sites are archived on CD-ROM disks for distribution to the user community.

Expected Results and Outputs of the ACTS Propagation Campaign

The expected results of the ACTS propagation campaign are summarized below:

- Ka-band propagation data
- A revised map of rain climate regions for North America
- Prediction models of rain and atmospheric attenuation and scintillation
- Fade and nonfade duration distributions
- Frequency scaling models
- Diversity models
- Multiple site analysis
- Mitigation schemes for propagation anomalies
- Contributions to regulatory organizations
- Modeling of the effect of antenna dish moisture (water and snow) on the link

The ACTS multiyear (at least two years), multisite campaign will produce ample propagation data. Presently, raw and processed data are. carefully archived by the ACTS Data Center for distribution to the user community. Upon the completion of the campaign, the propagation data bank will contain dual-channel beacon and radiometer measurements, rain rate measurements, and meteorological measurements (ambient temperature, barometric pressure, humidity records, etc.) for each site. The data bank will also include daily logs of each site.

Site rain-rate statistics are needed to predict rain attenuation on satellite links. Often such information does not exist for the location of interest and a rain . climate map is used to approximate site rain-rate statistics. The available rain climate maps for North America arc crude and in need of revision. Examples arc the ITU-R map, see Figure 5, and the global map [3]. ACTS multisite rain rate measurements will be used to improve existing rain climate maps, resulting in a better prediction of rain attenuation statistics at sites that lack rain-rate data.

in response to the recent surge of interest in low-margin applications, such, as very-smal]-apcrt urc terminals (V SAT), tools that can predict propagation effects in low- and medium-margin links will be developed. These effects include attenuation and scintillation.

Fade and nonfade statistics are useful information in the design of Earth/space links. Some information is available on this subject from previous studies, such as Olympus [2, Vol. 1]. The ACTS propagation campaign will provide more data on this issue, resulting in models that can predict fade- and nonfade-duration statistics. The ACTS experimenters will also determine the fade-duration distribution as a function of signal attenuation. This distribution will enable system designers to conveniently plan a suitable amount of fade margin for a system.

The ability to scale propagation-related statistics from one frequency to another is called *frequency scaling*. For example, at tenuation statistics arc scaled from 20 to 30 GHz. A simple model was developed for 20- and 30-GHz frequencies as a result of the Olympus experiment. This model depends on the ratio of the two frequencies [4] and works adequately during a storm, but it does not track the beginning and the end of the storm very well. This campaign's dual-frequency measurements are well suited for frequency scaling work, It is expected that this work will result in a frequency-scaling model that will accurately track an event for the duration of a storm.

The ACTS propagation campaign includes a three-site diversity experiment. A schematic depicting the geometry of the diversity experiment is given in Figure 6. The sites arc located in Laurel and Clarksburg, MD, and in Reston, VA. The distance between the sites arc 33, 31, and 55 km, and the elevation angle to the satellite is approximately 39°. The first site is equipped with a single-frequency (20-GHz) receiver, the second site is equipped with a dual-frequency receiver, and the third site, which is the ACTS propagation site in Reston, Virginia, is equipped with an APT. The diversity experiment will produce joint probability fade distributions, and these distributions will pertain to two-site. and three-site combinations.

Uplink power control is a means of mitigating rain attenuation. One of the ACTS propagation experimenters —Comsat Labs in Clarksburg, MD— completed an uplink power control experiment in early 1995.

One of the most important results of the ACTS propagation campaign is its contribution to regulatory agencies, particularly to the International Telecommunication Union. To address the propagation needs of the satellite communication community, ITU-R has made a recommendation on slant-path propagation. This recommendation, known as Rec. 618, contains methods and models for predicting slant-path effects caused by the atmosphere. Rec. 618 addresses a wide range of issues, including hydrometeor anti gaseous attenuation, scintillation, antenna gain distortion, dust and sand storm effects, and more, Reference [5] identifies some shortcomings of Rec. 618 and points out how ACTS experiments can help to remedy several of these shortcomings, In general, the ACTS campaign is expected to make contributions to Rec. 618 in the following areas:

- By measuring daily and monthly variations in gaseous attenuation, which were not taken into account in Rec. 618.
- By extending the range of the ITU-R rain attenuation model to percentage values beyond 1% of an average year, e.g., 5%.
- By simplifying the ITU-R method for frequency scaling and determining the short-term variations of attenuation ratios at two frequencies.
- By providing the ITU-R data on fade duration and a method to predict fade duration distribution.
- By determining how fade rates are distributed, and their correlation to fade depth, if any.
- By providing a cloud attenuation model.
- By improving the rather crude ITU-R rain climate map of North America.
- By providing measurements from the ACTS Florida site to case the shortage of tropical/subtropical data,

Although every onc of the ACTS propagation experimenters will contribute to the objectives of the campaign, each experimenter will focus on certain areas of special interest, Table 4 shows the sites with their associated areas of special interest.

Table 4. ACTS Experimenter Focus Areas

Site	Principal investigator	Focus Area
University of Alaska	C. Mayer	• Cloud effects • Scintillation
University of British Columbia	M. Kharadly	• Fade duration statistics • Scintillation effects • Melting layer contribution to propagation
Colorado State University	V. Bringi	• Rain and snow effects • Polarimetric radar predictions
Comsat (Maryland & Virginia)	A. Dissanayke	• Uplink power control • Wide-area diversity
Georgia Tech[i]	D. Howard	• Wideband propagation effects
university of South Florida[ii]	R. Henning	• Radiometric prediction schemes • Propagation models for subtropical regions
New Mexico State University[iii]	S. Horan	• Correlative analysis with TDRS ancillary data • Scintillation effects • Multiple site analysis
University of Oklahoma	R. Crane	• Rain rate and attenuation distribution models • Correlative analysis with climatological data • Condensation and snow on the antenna • Scintillation

[i]This site does not use an APT, and long-term statistics are not collected.
[ii]In partnership with Florida Atlantic. University, H. Helmken, principal investigator.
[iii]In partnership with Stanford Telecom, L. Ippolito, principal investigator .

Sample Results

This section provides some of the results of the ACTS propagation campaign to date. The purpose of this section is to present sample results only; it is not intended to be a comprehensive report on the campaign's findings.

Uplink Power Control

One of the objectives of this campaign is to develop tools for the mitigation of propagation-induced impairments. One such technique, open-loop uplink power control, has been evaluated by Comsat Labs using ACTS [6].

Open-loop power control entails the estimation of the uplink fade at an Earth station using a downlink signal and increasing the transmit power of the carrier to compensate for the uplink fade. Two key factors that determine the effectiveness of the open-loop power control are the detection of the correct downlink signal fade (or enhancement) and the frequency translation of this value to the uplink frequency.

An experiment was conducted using the ACTS satellite to investigate the limitations of the open-loop power control technique. The power control design is based on controlling the power at an IF stage using a linearized PIN diode attenuator. A power-controlled pilot carrier was transmitted from the NASA ground station in Cleveland, OH, and received at Comsat Labs in Clarksburg, MD. The power-control algorithm takes into account equipment-induced errors as well as those attributed to the propagation environment. The test period lasted about six months during which a sufficient number of rain events were encountered to evaluate the controller performance. It was found that under most conditions the power control accuracy could be maintained within approximately ±2.5 dB.

The accuracy of the control system is measured by comparing the observed power of the 20-GHz pilot signal with the observed power of the 20-GHz beacon signal at the receive end of the experiment, Comsat Labs, MD. The difference between the two power values constitutes the control error (first a power ratio is computed and then it is converted to dB). Figure 7, provided by Comsat Labs, shows the error statistics generated for the duration of the experiment. The control error for several exceedance probabil i tics ranging from 1 % to 99% arc plotted against the uplink fade. The statistics shown pertain to all rain events observed at the Cleveland site. Note that atmospheric effects at the receive site, Comsat, arc transparent to the experiment because the received pilot is compared to the received beacon signal. These two signals arc of 20 GHz frequency with a smal l frequency separation to allow interference-free detection of both signals.

Fade Statistics, Clarksburg, Maryland

Figure 8 shows the annual statistics of beacon attenuation at Clarksburg, MD, for one year, from Nov. 1993 to Oct. 1994. These measurements were made using the terminal provided by Comsat Labs. This figure also shows the ITU-R predictions based on surface rain rate measurements ---0.01% rain rate of 72 mm/hr. It is observed that the ITU-R model closely tracks the measured statistics of the rain attenuation.

Figure 9 shows the same scenario as in Figure 8 except that ITU-R predictions are based on the site's rain climate zone K with 0.01% rain rate of 42 mm/h. Clearly, the predictions are not close to the measured statistics. This observation substantiates the earlier claim that the IRU-R rain climate map for north America is not accurate.

APT and Radar Measurements, Fort Collins, Colorado

The Colorado site of the ACTS campaign, operated by Colorado State University at Fort Collins, is equipped with an S-band radar known as CSU CHILL radar. This radar is capable of making attenuation predictions approximately on the same path as the APT. Simultaneous measurements made by the two systems allow a comparison of the radar and APT measurements.

Figure 10 shows the APT beacon and radiometer measurements, i.e., attenuation with respect to free space (AFS), also known as total attenuation (rain and atmosphere), of a storm on June 20, 1994. The top chart is for 20 GHz and the bottom chart is for 27.5 GHz. Due to a deep fade, the 27.5 -GHz signal was lost (receiver loss of lock) for about 16 minutes. This signal was reacquired at 21:39 UTC. Note that radiometer estimates of signal attenuation are reasonable up to 10 dB of attenuation. Beyond 10 dB of attenuation, radiometer estimates do not match the receiver output.

Figure 11 shows the instantaneous total attenuation for beacon and radar measurements for the same day. Note that for the 27.5-GHz channel, there are no beacon measurements above 25 dB of loss, whereas radar measurements exist for well beyond this value.

Scintillation Measurements, Fairbanks, Alaska

The Alaska site of this campaign has the lowest path elevation angle among all the sites, At an elevation angle of only 9(', this site is subject to heavy scintillation events at certain periods. Figure 12 shows the received beacon power levels over a 1-hour time period on a day with heavy scintillation activity, August 16, 1994. Note the high level of scintillation with a peak-to-peak variation of about 7 dB.

Figure 13 shows the empirical distribution function (edf) of the standard deviation of the observation in a minute over the 1-hour data at the two measurement frequencies. The 27.5-GHz beacon distribution displays a higher mean value of the standard deviation.

Worst Month Statistics, Norman, Oklahoma

The annual worst month for attenuation by rain is defined to be the month within a year that has the largest fraction of time during which the attenuation on a propagation path exceeds some threshold of interest (larger time fraction of excess) [7]. The worst month is not a specific calendar month but the month that produces the most outage for a specified fade margin. The worst month in any calendar year may vary from one month to another as the attenuation threshold is changed. in climate regions with definite rainy seasons, the months that may be a worst month arc usually confined to the rainy season. Figure 14 shows the dual-frequency attenuation statistics for the worst month of 1994 at the Norman, OK, site.

Attenuation Statistics and Frequechy Scaling, Vancouver, British Columbia

Figure 15 shows the cumulative attenuation statistics for January 1994. Both 20- and 27.5-GHz statistics are shown. Also presented arc the ITU-R scaling model results. The frequency scaling model predicts attenuation at one frequency by using the attenuation at another frequency for the same probability level. The ITU-R rain attenuation frequency scaling model [8] is given as

$$A_2 = A_1 \left(\frac{\phi_2}{\phi_1}\right)^{1-H}$$

where

$$\phi = \frac{f^2}{1 + 10^{-4} f^2}$$

$$H = 1,12x10^{-3} \phi_2 (\frac{\phi_2}{\phi_1})^{0.5} (\phi_1 A_1)^{0.55}$$

and A_1 and A_2 arc the equiprobable values of rain attenuation.

Attenuation Measurements and Model Comparison, Las Cruces, New Mexico

Figures 16 a and b depict the annual total attenuation statistics for 20- and 27.5-GHz frequencies, respectively, for 1994. Also shown arc two rain attenuation prediction models of global and ITU-R. These models that predict rain attenuation (not total attenuation) are described in Reference 3. Gaseous attenuation is added to the rain attenuation models to make the models compatible with the measurements –measurements reflect total slant path attenuation. For both frequencies, the IT- R model over predicts attenuation whereas the global model under predicts attenuation. The site of these measurements, Las Cruces, is an arid region in the southwestern USA. This site is located in zone M of the ITU-R rain climate map, see Figure 5.

Fade and Fade-hration Measurements, Tampa, Florida

The Florida site of the ACTS propagation campaign is unique. in that it is the only site with subtropical climate. Most of the existing Ka-band propagation data in the world come from temperate regions, mainly from Europe, U.S., Canada, and Japan. Therefore, data from the Florida site are very important for developing models that arc also accurate in subtropical regions of the world. Deep fades are expected to occur with a higher time percentage in subtropical and tropical climates than temperate zones.

Figures 17 a and b show the percentage of time a given level of attenuation is exceeded for attenuation levels of 10, 20, 30, and 35 dB for the summer months of June–September 1994. The 20 and 27.5 GHz results arc shown in Figures 17 a and b, respectively. Note that the 10-dB fade level is exceeded with a probability of about 1.5% for the 27.5 GHz signal in July 1994.

Fade duration statistics are important link parameters in the design of a communication system [9]. A good knowledge of the fade duration distribution is important for the assessment of a satellite communication system's channel dynamics: What is a typical link outage duration? How often do link outages exceeding a given duration occur?

Figures 18 a and b show the average fade duration values for the summer months of June-Scpten~ber 1994 for the same fade levels as in Figure 17, for 20 and 27.5 GHz signals, respectively. Average, or mean, fade duration is calculated by dividing the total fade period by the total number of fades for a given threshold, The plots shown in Figure 18 do not include very short (few seconds) deep fades. Figure 18 should be viewed as a preliminary result; more elaborate statistics will be produced in the near future. Note that the average fade duration for the 27.5-GHz signal, with a fade threshold of 10 dB, is near 20 minutes.

Summary

This paper described an experimental campaign for collecting Ka-band propagation data using ACTS. The objective of the experiment is to characterize satellite communication channels, and the campaign consists of ten fixed sites and a mobile terminal. Only the measurements using the fixed sites were addressed in this paper. Reference 10 describes the mobile experiment.

Seven of the ten fixed sites use ACTS propagation terminals provided by NASA. These terminals are identical and share the same software for data preprocessing. The data collected by these sites are archived at the ACTS Data Center for distribution to the user community.

The sites began collecting data in late 1993 and data analysis began in 1994. Sample measurements, analyzed data, and preliminary results have been reported in Figures 7–18. In the second half of 1995 and during 1996, many refined statistics and results are expected to be developed and distributed by the ACTS propagation campaign.

Acknowledgment

The author would like to express his gratitude to the ACTS propagation experimenters. Without their tireless efforts and endless patience this campaign would not have succeeded. The measured data reported in this paper, Figures 7–18, are the courtesy of the ACTS propagation experimenters: Figures 7–9 were supplied by Dr. Asoka Dissanayake of Comsat Lab. Figures 10 and 11 were supplied by Mr. John Beaver of Colorado State University. Figures 12 and 13 were supplied by Dr. Charles Mayer of the University of Alaska. Figure 14 was provided by Dr. Robert Crane of the University of Oklahoma. Figure 15 was provided by Dr. Moss Kharadly of the University of British Colombia, Figure 16 was supplied by Dr. Louis Ippolito of Stanford Telecom and Dr. Stephen Horan of New Mexico State University. Figures 17 and 18 were provided by Dr. Henry Helmken of Florida Atlantic University and Rudolph Henning of the University of South Florida. Detailed up to date results of the ACTS propagation campaign are provided by the experimenters in reference 11.

Many thanks to our sponsors at NASA Headquarters for both financial and moral support of our efforts. I would also like to thank Bob Bauer of NASA Lewis Research Center for being so supportive of the campaign, Bob has been an effective liaison between the propagation community and the ACTS program.

This campaign is much indebted to our two workshop chairmen, Drs. Robert Crane and David Rogers, who skillfully moderate our plenary sessions to fruitful outcomes. Credit is due to David Westenhaver whose excellent support of our propagation terminals has contributed to the success of our measurements.

The much needed assistance received from Kris Suwitra and Mardy Wilkins in technical and administrative management of this campaign is gratefully acknowledged.

1 would also like to thank Dr. Robert Crane for reviewing this paper and providing me with very useful remarks.

The research conducted in this paper was performed at the Jet Propulsion laboratory, California Institute of Technology, under a contract with the National Aeronautics and Space Administration.

References

1. B. Arbesser Rastburg, "Progress Report on Ol ympus Propagation Experiments," *Proceedings of NAPEX XVIII,* JPL Publication 94-19, pp. 7-10, August 1, 1994.

2. *OPEX Reference Book,* Volume 1–5, ESA WPP-083, November 1994.

3. L. Ippolito, *Propagation Effects Handbook for Satellite System Design,* NASA Reference Publication 1082 (04), pp. 3-23, February 1989.

4. W. Stutzman, "Slant Path Propagation Models Resulting from Olympus Experiments in the U.S.," *Proceedings of NAPEX XVIII,* JPL Publication 94-19, pp. 11-45, August 1, 1994.

5. F. Davarian, "Opening Remarks," *Presentations of APSW VI,* JPL D- 12350, pp. 3-7, December 1994.

6. *A CTS Up-Link Power Control Experiment,* Fi nal Report, Comsat Laboratories, SSTD/95–2 17, March 1995.

7. R. Crane, "Worst-Month Rain Statistics: A New Approach," *Radio Science,* Vol. *26, No. 4,* pp. *801-820,* July-August 1991.

8. 1992 *CCIR Recommendations,* RPN Series, Geneva, p. 2S2, October 1992.

9. F. Davarian, "Earth-Space Links and Facie-Duration Stati sties," to be published in the *A GARD Conference Proceedings*, Athens, Greece, September 1995.

10. J. Goldhirsh and W. J. Vogel, "Mobile Prop agation Modeling Results Using ACTS and Other Measurements," *Proceedings of NAPEX X1X,* JPL Publication 95-/5, 1995.

11. F. Davarian, editor, *Proceedings of NAPEX XIX and APS W VII,* JPL Publication 95-15, August 1, 1995.

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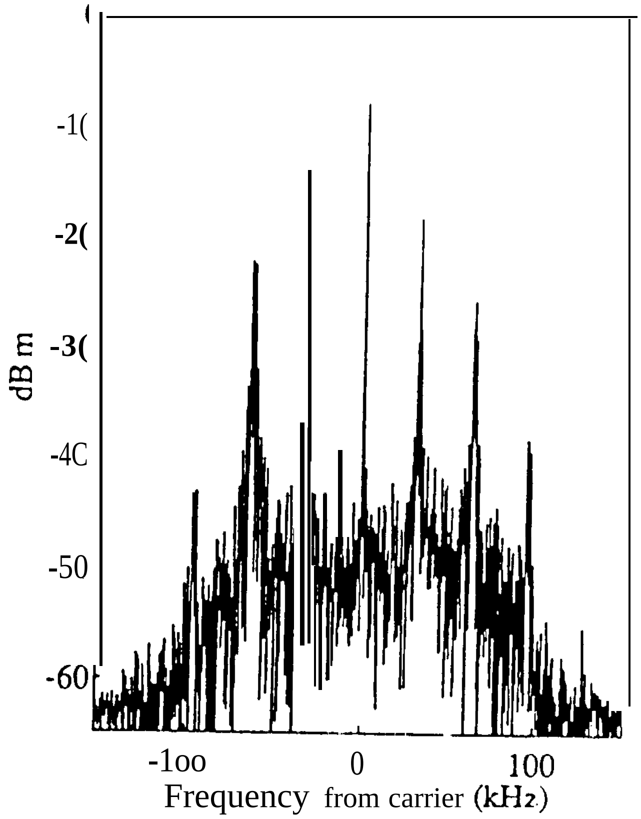


FIGURE 1

Measured Power Spectral Density of the Downlink Beacon (20 GHz) .

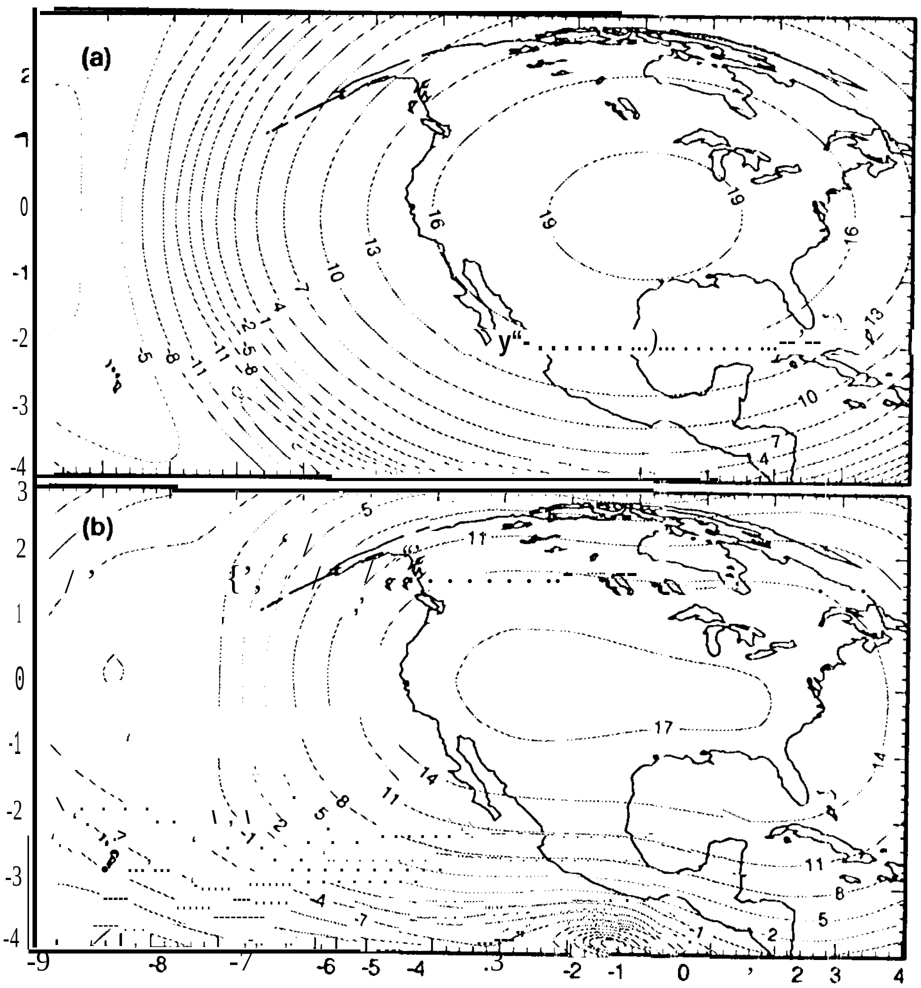


Figure 2

Radiation Patterns of ACTS Propagation Beacons
(a) downlink (b) upl ink

ACTS PROPAGATION TERMINAL

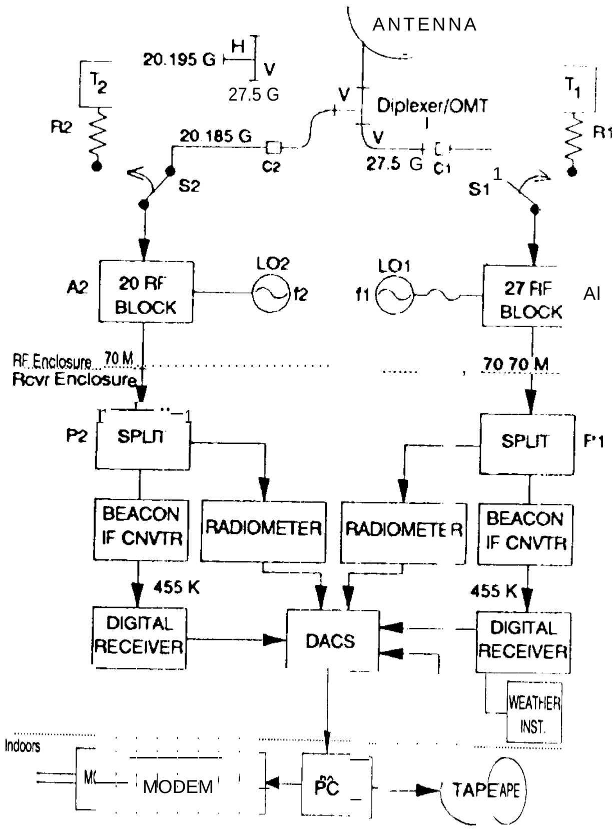


Figure 3

Block Diagram of the ACTS Propagation Terminal.

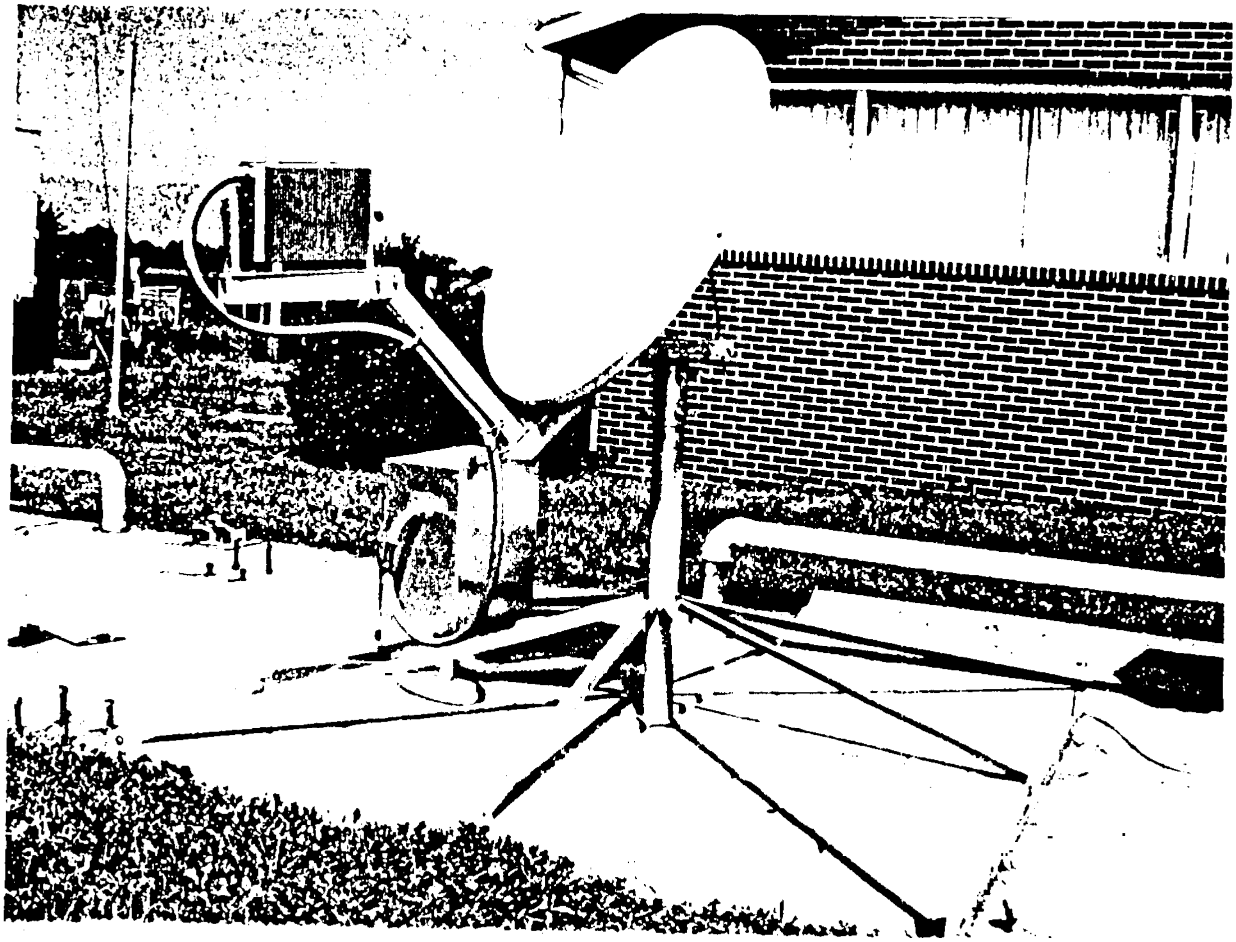


Figure 4

A View of the ACTS Propagation Terminal .

ITU-R Rain Zones& Rainfall Rate Exceeded (mm/h)

% of Time	C	D	E	K	M	N
1.0	0.7	2.1	0.6	1.5	4	5
0.1	5	8	6	12	22	35

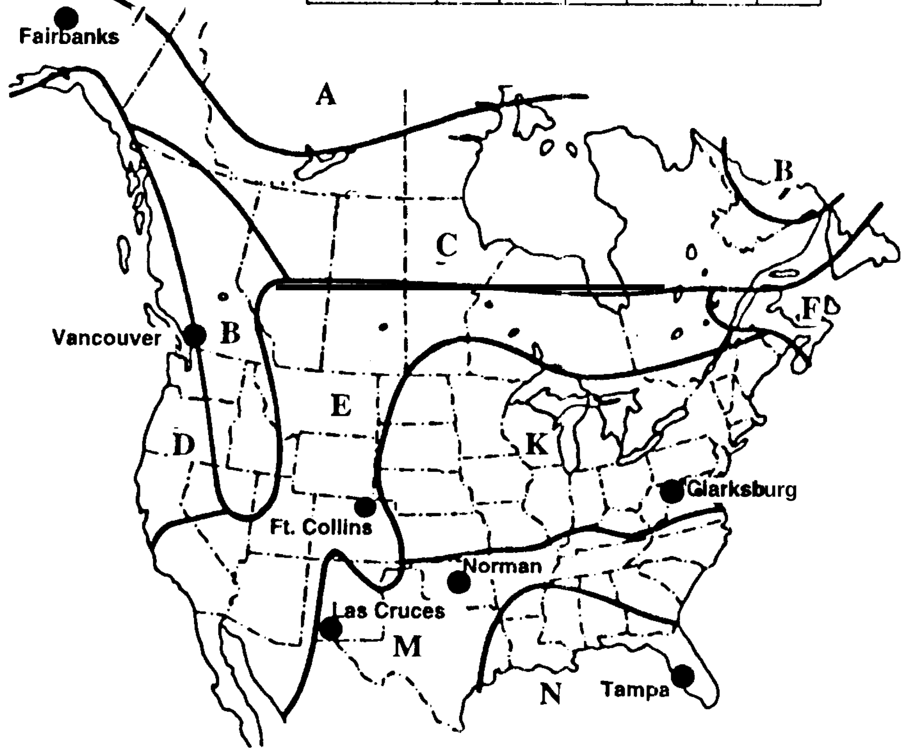


Figure 5

ACTS Propagation Measurement Sites Shown on the ITU-R Rain Climate Map.

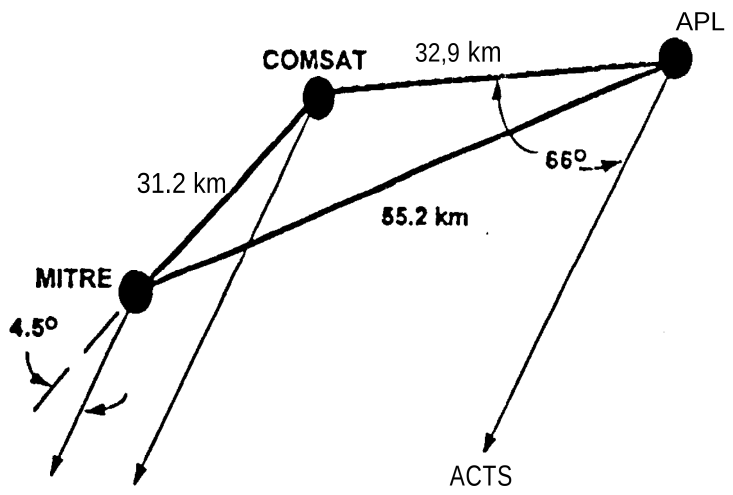


Figure 6

Geometry of APL- COMSAT-Mitre Diversity Links.
(APL: Laurel, MD; COMSAT: Clarksburg, VA; and Mitre: Reston, VA.)

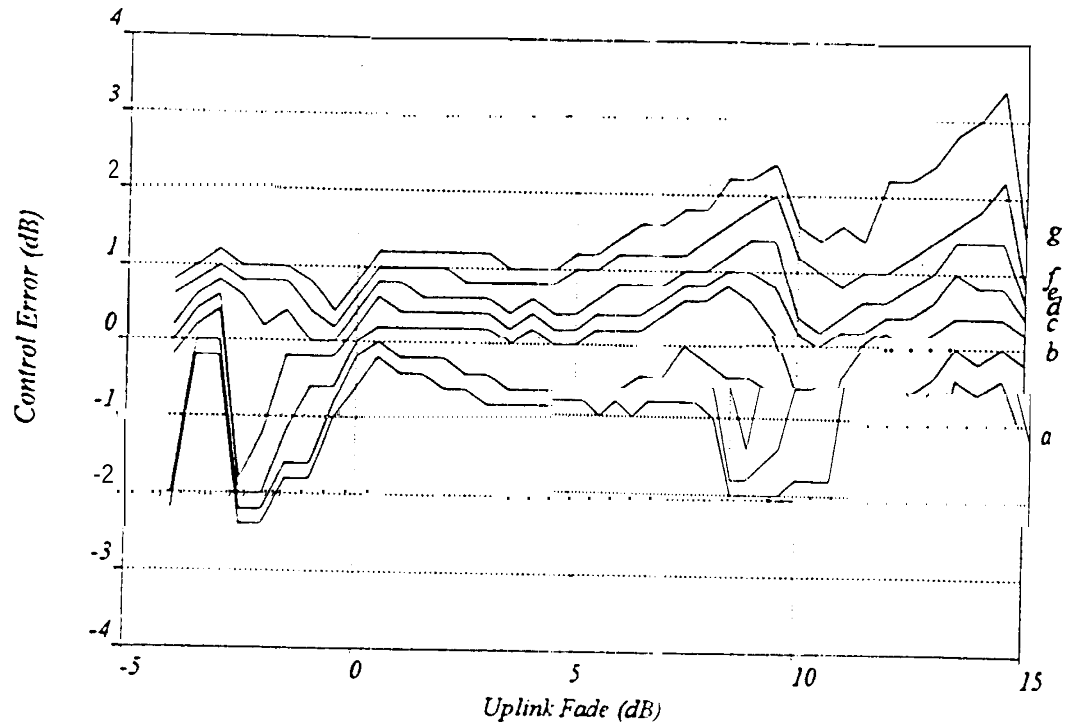


Figure 7

Distribution of Power Control Error
(a: 99%, b: 95%, c: 75%, d: 50%, e: 25%, f: 5%, g: 1%).

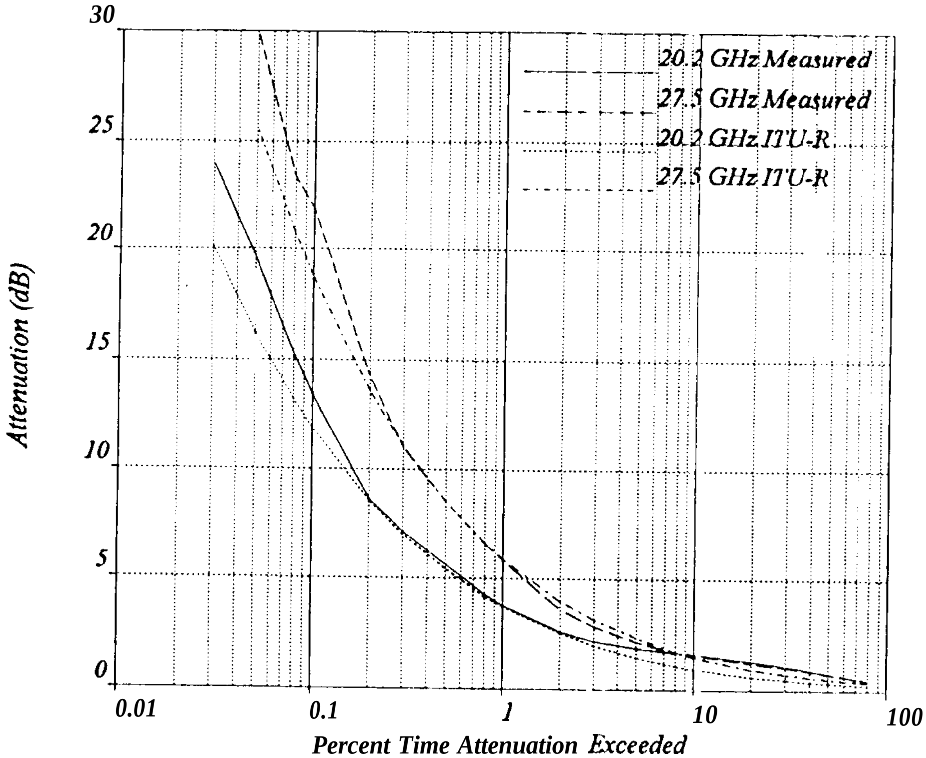
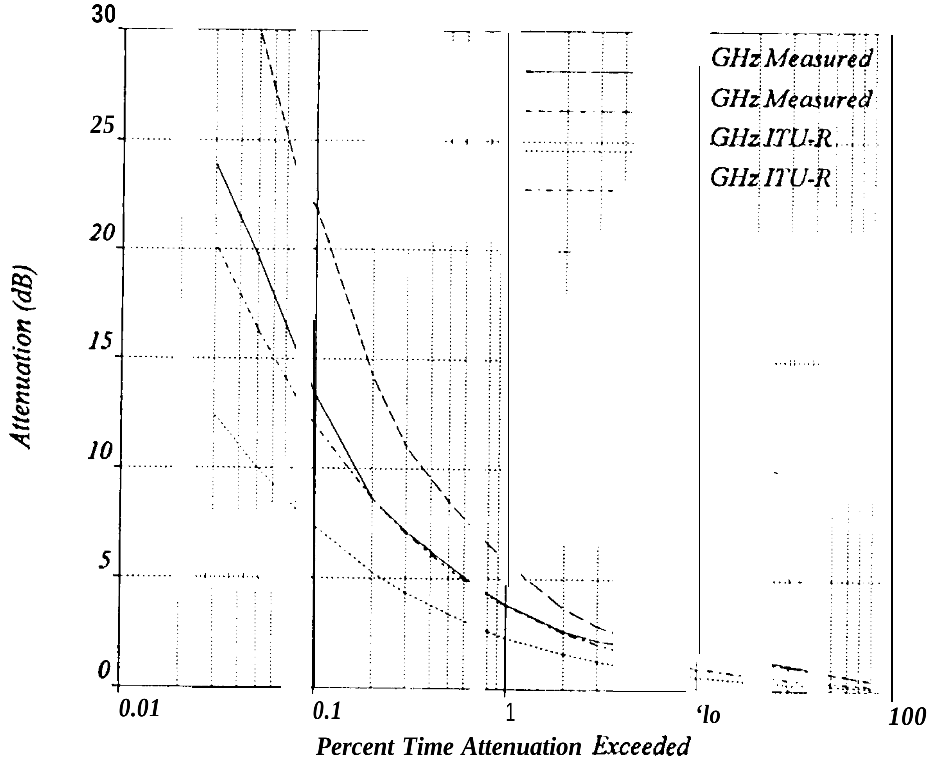


Figure 8

Cumulative Distribution of 20- and 27.5 GHz Attenuation at Clarksburg, MD, fom Nov. 1993-October 1994; Measured 0.01% rain rate: 72 mm/h.



from Nov. 1993- Oct. 1994; Rain Zone K 0.01% Rain Rate: 42 mm/hr

Figure 9

Cumulative Distribution of 20- and 27.5 GHz Attenuation at Clarksburg, MI), from Nov.1993-October 1994; ITR-R 0.01% rain rate: 42 mm/h (rain zone K).

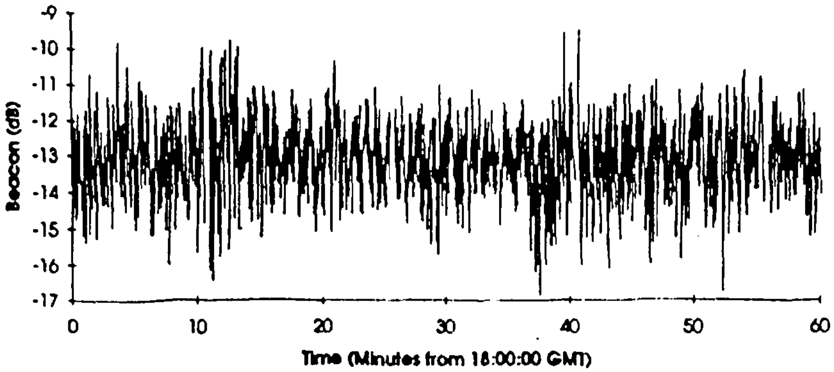


Figure 1.2

Measured 27-GHz Beacon Power Level Over a One-Hour Period at Fairbanks, AK; August 16, 1994.

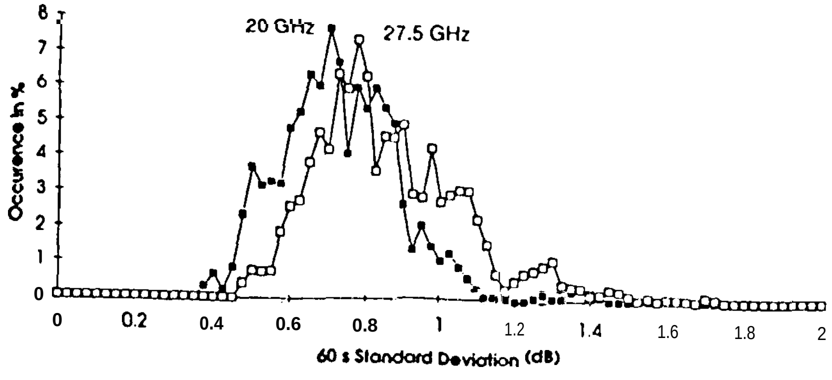


Figure 13

Emperical Distribution Function of Scintillation Intensity Over the Same One-Hour of Data as Figure 12.

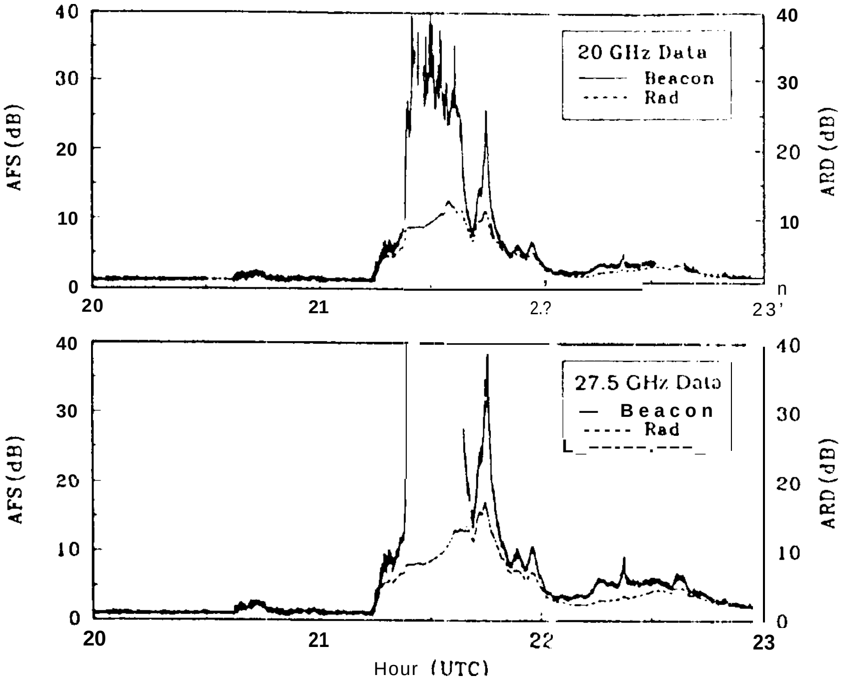


Figure 10

June 20, 1994, Rain Event at Fort Collins, CO;
APT Measured Attenuation and Sky Noise Temperature
as a Function of Time.

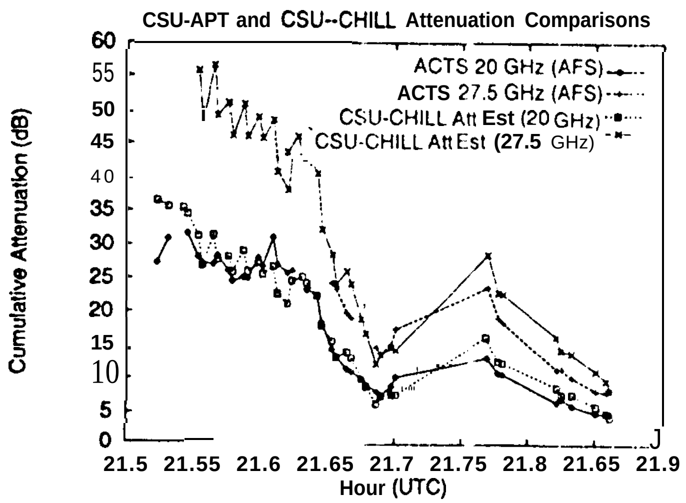


Figure 11

Comparison of Measured APT Attenuation and Attenuation
Estimates from CSU-CHILL S-Band Radar Data for the
June 20, 1994 Rain Event Shownin Figure 10; Site:
Fort Collins, CO.

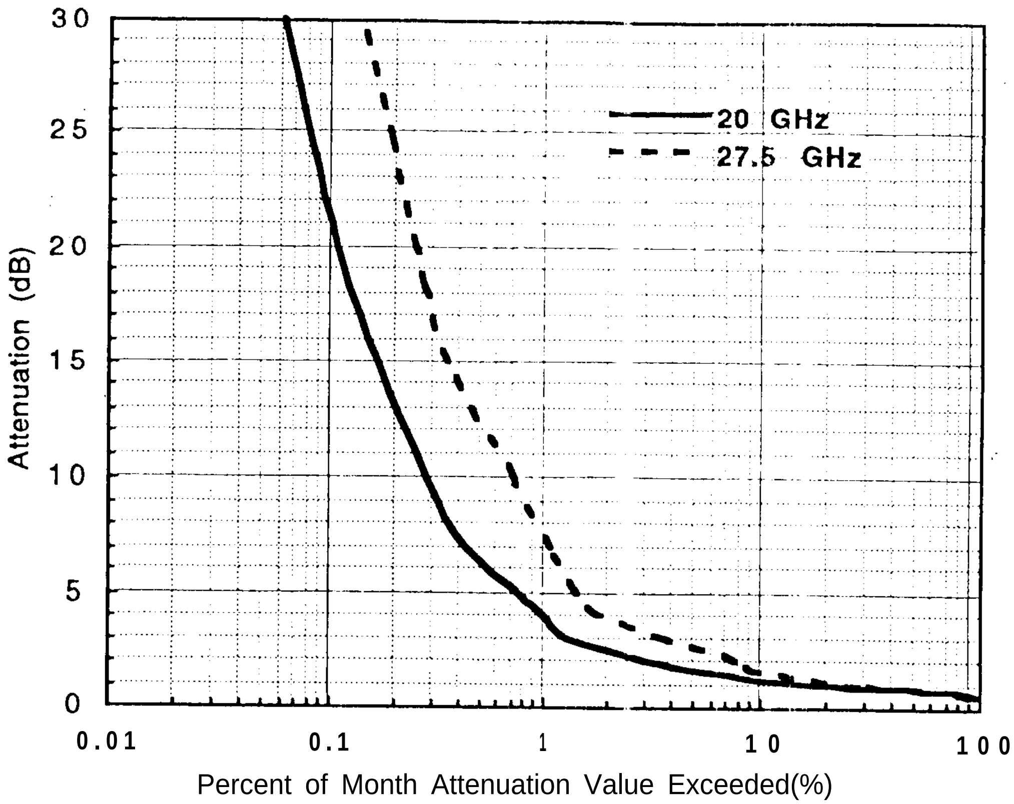


Figure 14

Attenuation Statistics for the Worst Month on the Measurement Year 1994; Site: Norman, OK.

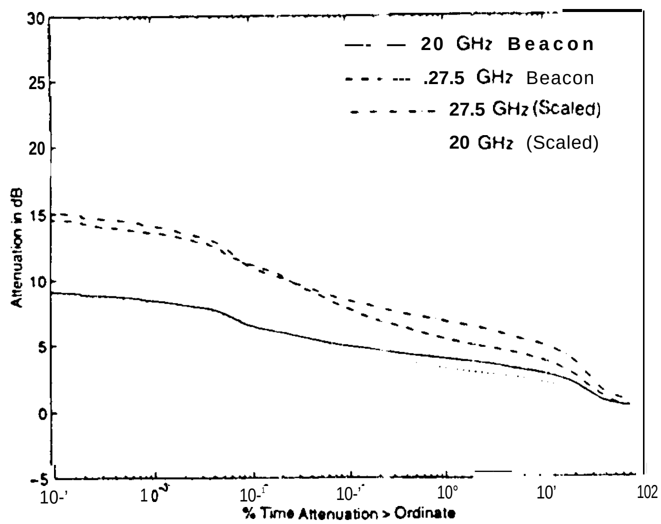
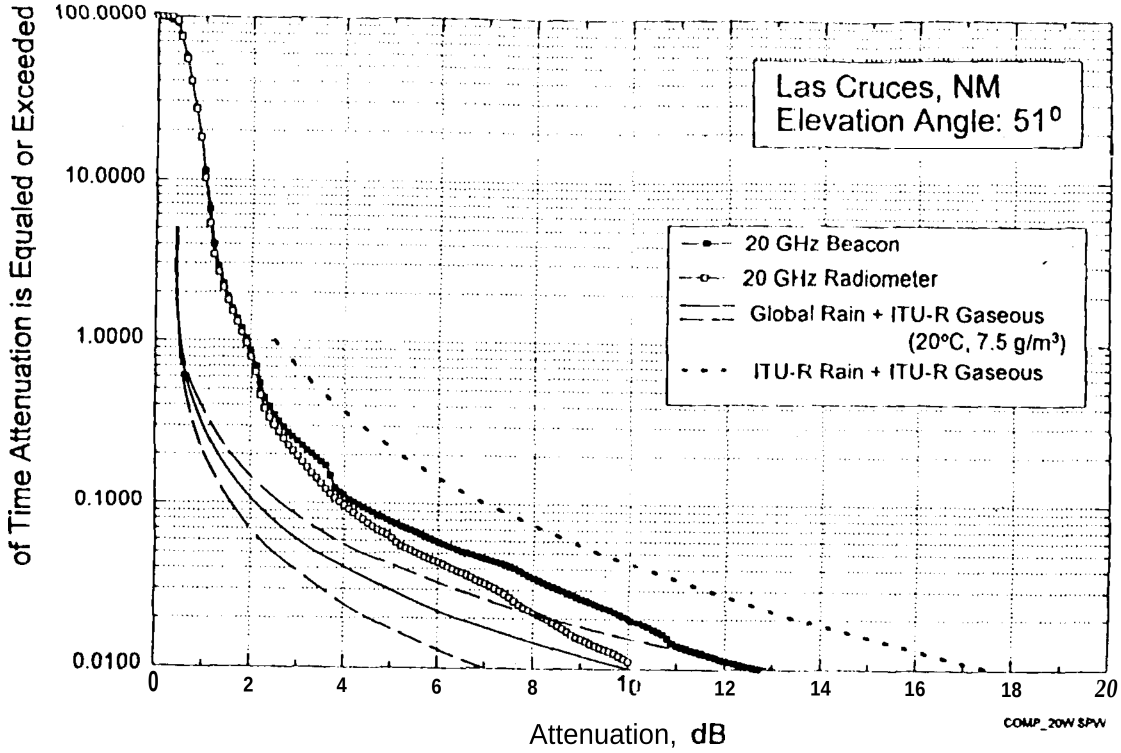


Figure 15

Cumulative Distribution Functions Comparing 20- and 27.5 GHz Beacon Attenuations with the ITU-R Frequency Scaling Model of Rain Attenuation; January 1994; Site: Vancouver, BC.

(a)



(b)

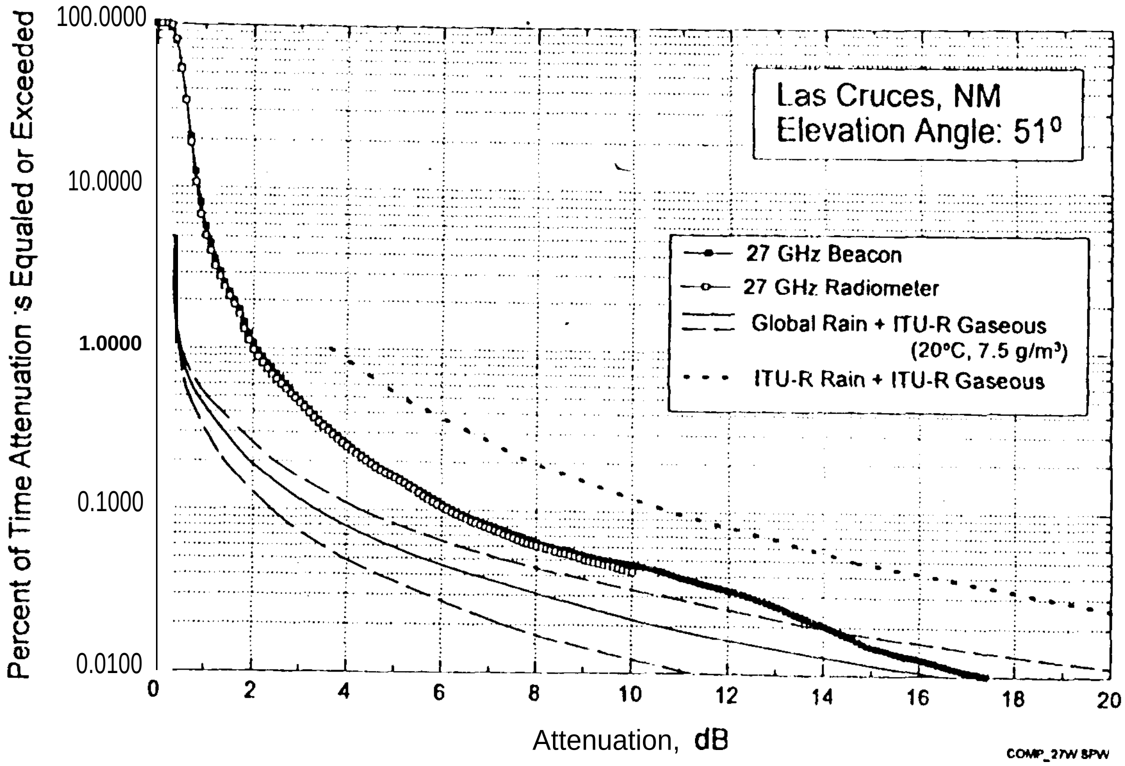


Figure 16

Measured Annual Attenuation Statistics for the Measurement Year 1994 are Compared to Global and ITU-R Rain Attenuation Prediction Models (the global model has been represented by its mean and upper and lover bands;) Site: Las Cruces, NM;
a: 20 GHz, b: 27.5 GHz.

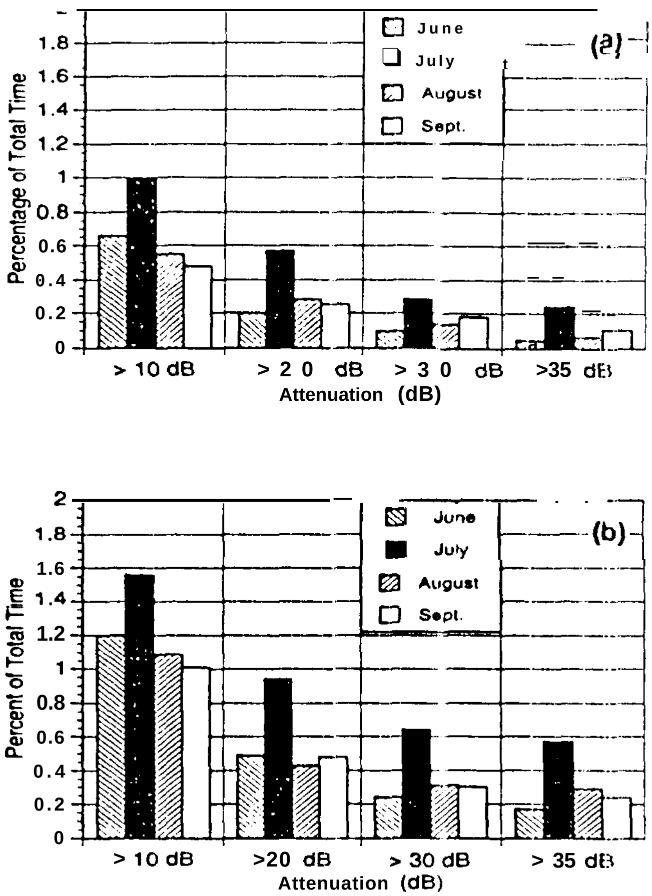


Figure 17

Monthly Percentage of Time that Attenuation Level is Exceeded from Tampa, Florida, Summer 1994: a) 20-GHz Fade Statistics; b) 27 .5-GHz Fade Statistics.

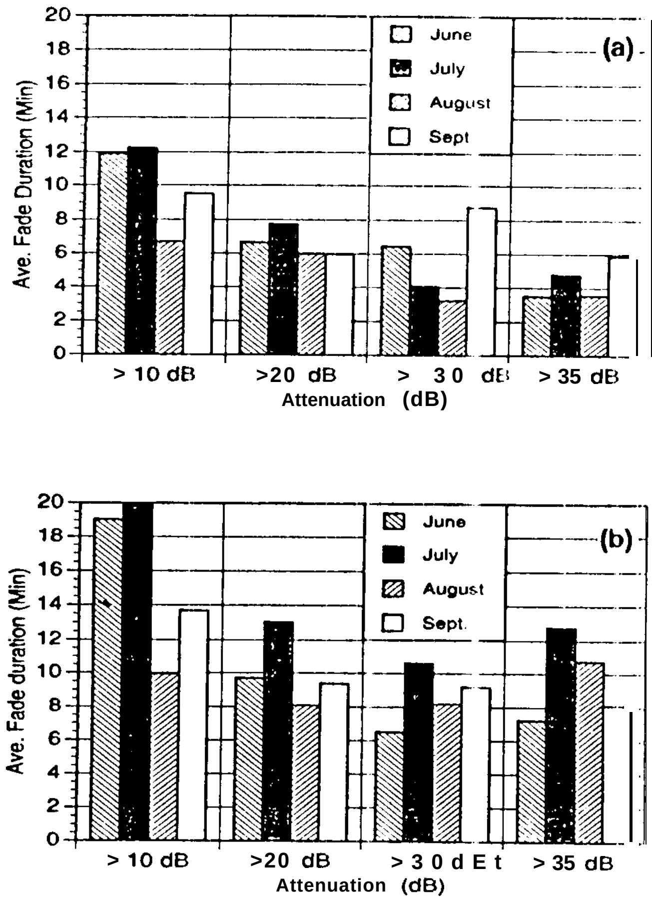


Figure 18

Mean Fade Duration for the Measurements of Figure 17. (Mean fade duration is calculated by dividing the total fade period by the total number of fades for a given threshold, i.e., 10, 20, 30, and 35 dB).